National Aeronautics and Space Administration

Modeling the Relationship Between Porosity and Permeability During Oxidation of Ablative Materials

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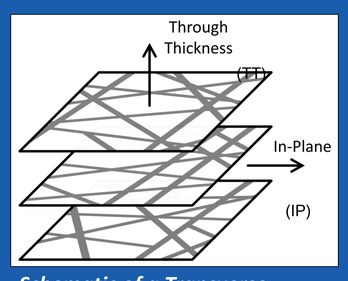
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Overview

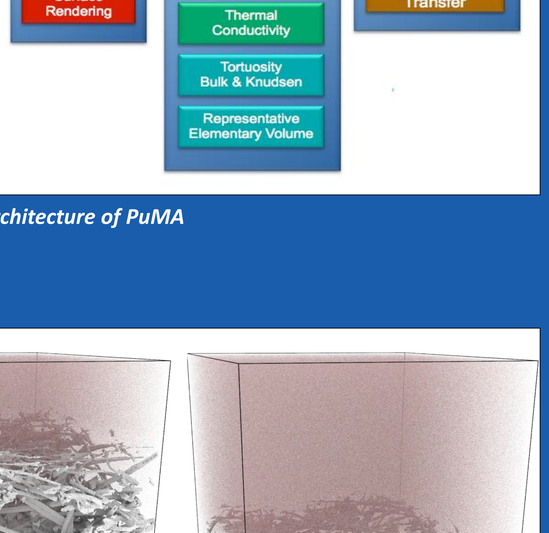
The ablative materials used in thermal protection systems (TPS) undergo oxidation during atmospheric entry which leads to an in-depth change in both permeability and porosity. These properties have a significant affect on heat transfer in a TPS during entry. X-ray micro-tomography has provided 3D images capturing the micro-structure of TPS materials. In this study, we use micro-tomography based simulations to create high-fidelity models relating permeability to porosity during oxidation of FiberForm, the carbon fiber preform of the Phenolic Impregnated Carbon Ablator (PICA) often used as a TPS material. The goal of this study is to inform full-scale models and reduce uncertainty in TPS modeling.

Micro-Structure of FiberForm

FiberForm is a transverse isotropic material composed of randomly oriented fibers with an average diameter of 11µm. It is strongly inhomogeneous with large variations in material properties at the microscale. Its porosity generally ranges from 85% to 91% [1].



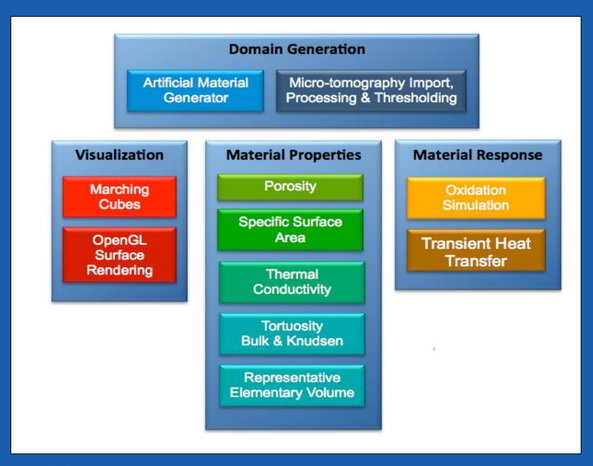
Schematic of a Transverse Isotropic Material



Microstructure of FiberForm Visualization Credit: Timothy Sandstrom

Porous Materials Analysis (PuMA)

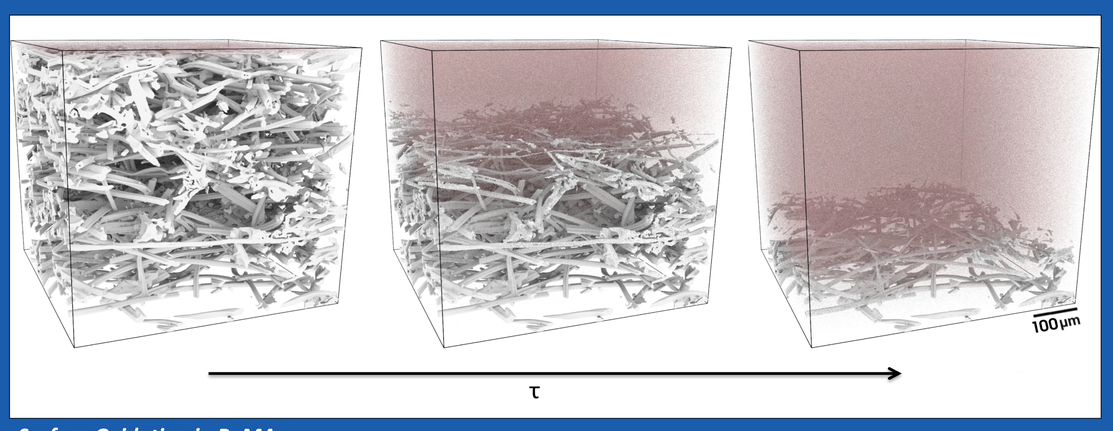
PuMA [2], a NASA software for micro-tomography analysis, was used to calculate porosity and simulate uniform oxidation using micro-tomography images of FiberForm. A gray-scale threshold value was specified to distinguish between the solid and void space.



Architecture of PuMA

Oxidation Simulation

The oxidation model in PuMA simulates diffusion through porous media as a random walk of oxygen particles with a sticking probability law for surface reactions [2,3].



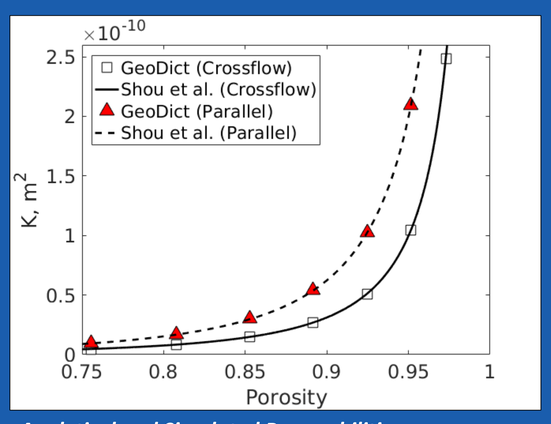
Surface Oxidation in PuMA

Permeability Calculations

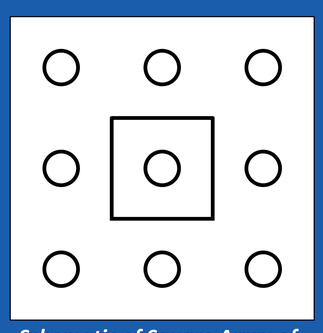
Permeability was calculated by simulating creeping flow using an explicit jump method in GeoDict [4], a commercial software for micro-structure analysis. The micro-structure was determined using a similar thresholding method to that in PuMA.

Verification using Array of Cylinders

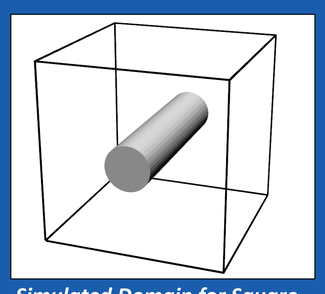
Permeability calculations were first done on a square array of cylinders for verification. The porosity was varied by changing the radius of the cylinders and keeping the domain size constant. The results were compared to a deterministic model from Shou et al. [5].



Analytical and Simulated Permeabilities



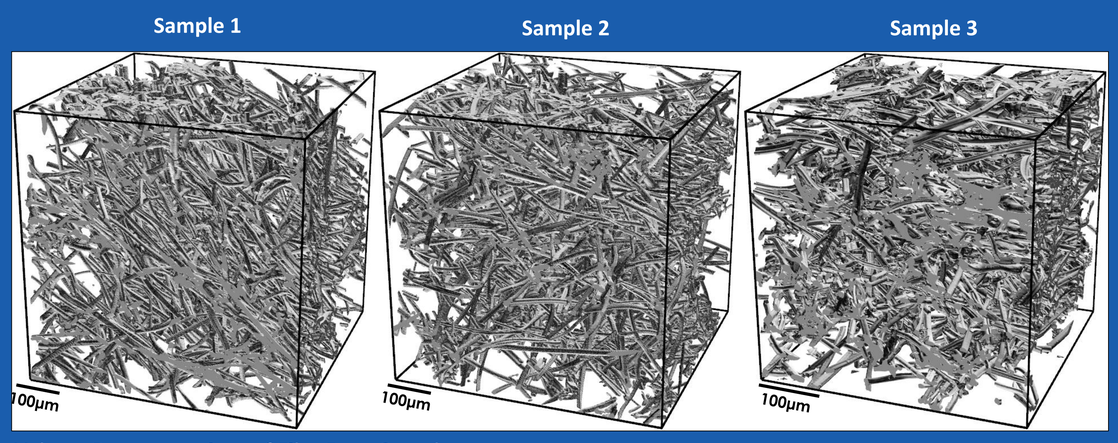
Schematic of Square Array of Cylinders



Simulated Domain for Square Array of Cylinders

Characterization of Samples

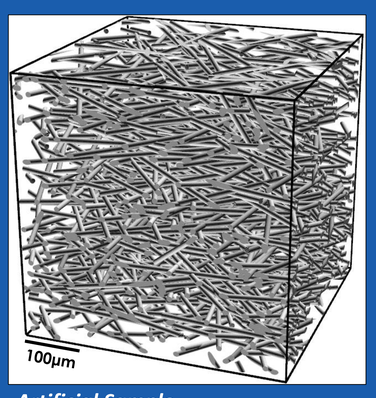
Tomography images for three samples of FiberForm were generated using the Advanced Light Source at Lawrence Berkeley National Laboratory. The first two samples had porosities of 89%, while the third sample had a porosity of 85%. The domain size was 512 voxels for samples 1 and 2, and 400 voxels for sample 3. Each sample had a voxel size of 1.3µm.



Volume Representations of FiberForm Samples

Artificially Generated Sample

An was artificially generated using PuMA. The artificial sample consists of 11µm diameter cylinders and has a porosity of 89%. The sample is transverse isotropic with a domain size of 512 voxels and a voxel size of 1.1µm.

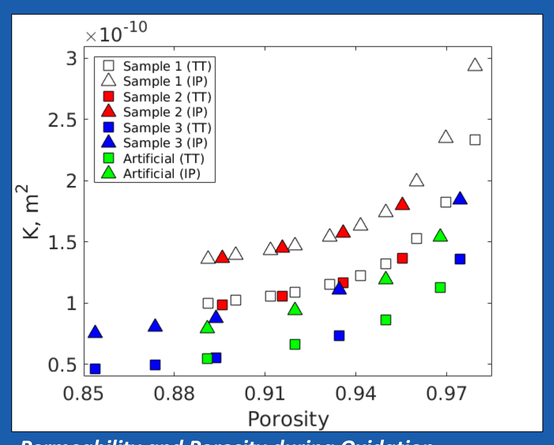


Artificial Sample

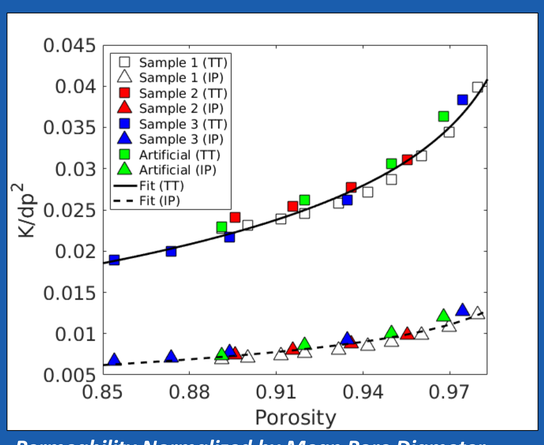
Normalization and Curve Fitting

The permeabilities were normalized by the square of the mean pore diameter. TT mean pore diameter was calculated by fitting spheres into the voids using GeoDict [6]. The IP pore diameter was calulated using an equation from Sampson and Urquhart [7]:

$$\frac{d_{p,TT}}{d_{p,IP}} = \frac{\sqrt{\varepsilon}}{2}$$



Permeability and Porosity during Oxidation



Permeability Normalized by Mean Pore Diameter

Curve Fit

$$\frac{k}{dp^2} = \frac{-0.64\ln\left(\frac{1-\varepsilon}{1+a\varepsilon}\right) + \left(\frac{1-\varepsilon}{1+a\varepsilon}\right) - 0.737 - 0.25\left(\frac{1-\varepsilon}{1+a\varepsilon}\right)^2}{b}$$

$a = 3,\ b = 63$ for TT
$a = 2,\ b = 215$ for IP

References

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Acknowledgments

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